

Testing of 90° Beam-Line Prototype at 55 MeV Electron Linac

Nuclear Engineering Division

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by
Roman Gromov, Matt Virgo, Sergey Chemerisov, and George Vandegrift
Nuclear Engineering Division, Argonne National Laboratory

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CONTENTS

1	INTRODUCTION	1
2	SIMULATION.....	1
3	PROTOTYPE LAY-OUT.....	3
4	SYSTEM LIMITATIONS	5
5	EXPERIMENTAL RESULTS.....	5
6	CONCLUSIONS.....	8
7	REFERENCES	8

FIGURES

1	Beam envelopes at 90° bend for 2.5% energy spread for two normalized beam emittances: 500 and 1500 mm-mrad.....	2
2	Beam envelope at 90° bend for beam transport with 10% of energy spread and 100 mm-mrad emittance.	2
3	Design of 45° bending magnet, top view.....	3
4	Top view of the prototype design.	4
5	90° bend installed in the lab.....	4
6	Beam image acquired by OTR camera at the 90° bend exit.	6
7	Beam intensity after passing of 90° band based on beam energy spread vs. settings of 90° bend for separate energies.	7
8	Changing of beam horizontal position and transport coefficient versus energy deviation.....	7

TABLE

1	Main bending magnet parameters.....	5
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1 INTRODUCTION

Argonne National Laboratory, in cooperation with NorthStar Medical Technologies and Los Alamos National Laboratory, is developing a technology for the production of Mo-99 via photonuclear reaction on a Mo-100 target [1, 2]. The new facility will utilize electron accelerators with high beam power. To increase the efficiency and uniformity of Mo-99 production, the target will be irradiated from two opposite sides. This approach requires two electron accelerators to be installed to produce electron beams and irradiate the target from opposite directions. To protect the electron accelerator from Bremsstrahlung radiation from the opposite accelerator, a 90° achromatic bend is proposed [3]. This bend consists of two 45° bending magnets with two quadrupole lenses installed between them. This approach will help to deliver a beam to the target that has significant energy spread.

2 SIMULATION

The 90° achromatic bend consists of two 45° bending magnets to turn the electron beam and quadrupole lenses with a magnetic field gradient to compensate for beam dispersion due to energy spread. The classical two-bend achromatic approach uses one quadrupole lens between the two bends. Use of two quadrupole lenses would help to increase acceptable beam energy spread. Since the final design of the accelerators is not known yet, and the beam parameters are not measured, computer code simulations were performed for a beam with emittance of 500 and 1500 mm-mrad, which are within reasonable expectation for an electron linear accelerator similar to the one used in the testing of the beam line prototype at Argonne National Laboratory. The simulations also assumed a relatively narrow energy spread of $dE=\pm 2.5\%$.

The simulations were used to determine the envelope of the beam in the bend. For beam energy of 40 MeV, an integrated quadrupole gradient of 0.247 T is required for achromatic transport. The emittance of the beam is not known with certainty, but the range of 500 to 1500 mm-mrad (normalized) is consistent with what has been historically observed in electron accelerators. First-order matched beam envelopes for these conditions are shown in Figure 1 for an energy spread of $\pm 2.5\%$.

For conditions where the beam is not matched, the envelope will not be symmetric at the center of the system. Given the practical constraints of the beam line, ideal matching may not be achievable. If that is the case, the measured beam size is expected to be larger or smaller at the exit of the system.

To test the beam transport through a 90° bend for a large beam energy spread, the particle tracking code Parmela was used. An input beam with a normalized emittance of 1000 mm-mrad and a distribution beam energy half-width of 10% was used. With these conditions, the beam envelope in Figure 2 was calculated.

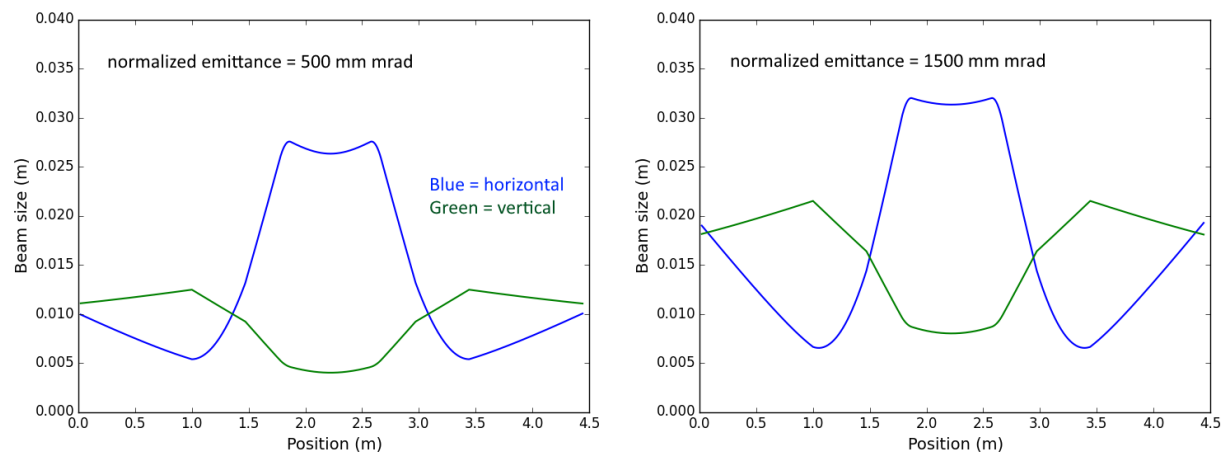


FIGURE 1 Beam envelopes at 90° bend for 2.5% energy spread for two normalized beam emittances: 500 and 1500 mm-mrad.

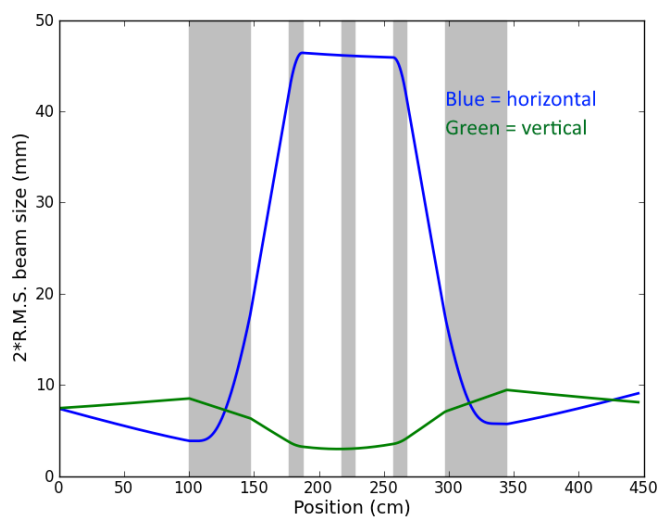


FIGURE 2 Beam envelope at 90° bend for beam transport with 10% of energy spread and 100 mm-mrad emittance.

A beam envelope simulation was performed to estimate the minimal aperture of the vacuum chamber. Based on the above results, the minimum horizontal aperture of the vacuum chamber should be at least 35 mm for a beam energy spread of $\pm 2.5\%$ and at least 47 mm for a beam energy spread of $\pm 10\%$. In practice, the energy spread of the beam that is used is always smaller than $\pm 10\%$, so the limitation for the horizontal aperture of vacuum chamber should not be a problem.

3 PROTOTYPE LAY-OUT

For the testing of a 90° beam-line prototype, the bending magnets are designed to have a rectangular shape (Figure 3). The vacuum chamber has a straight line for through-pass of electrons, a 60° bend, and an opposite flange for an optical port. Control of the beam transverse profile is based on an optical transmitted radiation (OTR) camera, which had successfully been used in beam size/position monitoring previously [4].

The experimental set-up was installed in the linac vault of LEAF (Low Energy Accelerator Facility) at Argonne National Laboratory. At the exit of the accelerating structure, a quadrupole doublet focuses the beam into the entrance of the bend (Figures 4 and 5). The 90° bend prototype was assembled from two 45° bends (Table 1) and two quadrupole lenses with aperture of 5 cm. The 45° bends are water-cooled with water interlocked power supplies. An aluminum window is installed at the end of the vacuum chamber. The image of the beam is directed to the aluminum plate and imaged by the OTR camera. The beam transverse profile and position were acquired from the OTR image of the beam.

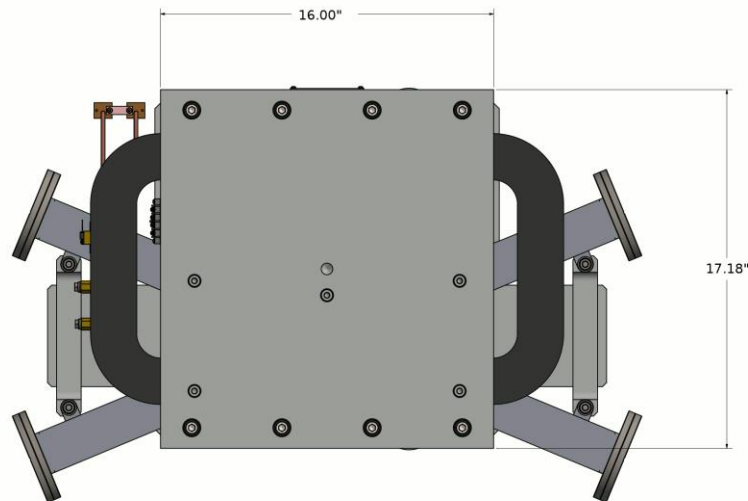


FIGURE 3 Design of 45° bending magnet, top view.

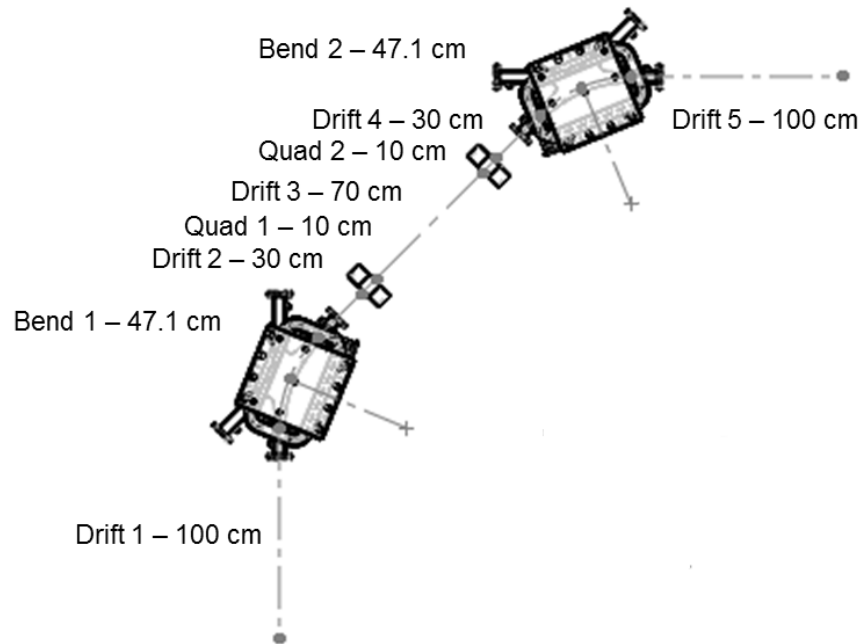


FIGURE 4 Top view of the prototype design.

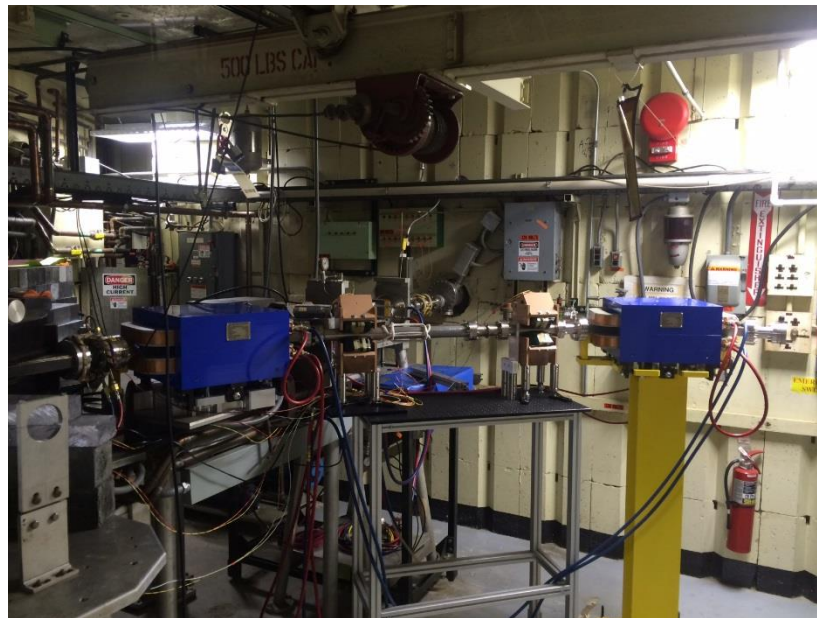


FIGURE 5 90° bend installed in the lab.

TABLE 1 Main bending magnet parameters.

Magnet shape	Square
Bend radius	60 cm
Bend angle	45°
Edge angles	22.5°
Linear range	3.3 kG

4 SYSTEM LIMITATIONS

While 45° bending magnets with vacuum chamber bends were manufactured for these tests, quadrupole magnets for the prototype were borrowed from existing stock of the standard beam optics in LEAF. The quadrupole lenses have the gap for a 2-in. vacuum chamber nipple. Therefore, the vacuum chamber aperture was restricted to 2 in. (or about 5 cm) of the beam transverse size. If the beam energy is 40 MeV, and electrons of this energy are passing at the center of the vacuum chamber, the maximum possible deviation from the main energy can be estimated from the equation for a right-angle magnet and some drift space behind:

$$\begin{pmatrix} x \\ x \end{pmatrix}_l = \left[\begin{pmatrix} 1 & R \sin(\phi) \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x \\ x \end{pmatrix}_0 + \frac{\Delta p}{p_0} \cdot \begin{pmatrix} -R(1 - \cos(\phi)) \\ -2 \tan(\phi/2) \end{pmatrix} \right] \cdot \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix};$$

where R is the bending radius, ϕ is the bending angle, and L is the drift space. For a 40 MeV beam and vacuum chamber aperture of 2 in., the maximal energy deviation is ± 1.5 MeV ($\pm 4.2\%$).

5 EXPERIMENTAL RESULTS

The beam energy profile was measured by a spectrometer installed in front of the 90° bend prototype. This spectrometer has the limitation of the top energy measurements being 40 MeV; therefore, all experimental runs and measurements were performed in the energy range of 33-40 MeV. An accelerated beam has close to a round shape with transverse size of about 5 x 5 mm full-width at half maximum (Figure 6). The exit energy of the electron beam was controlled by changing the amplitude of the injector pulse current (beam loading), which was in the range of 0.5-0.8 A.

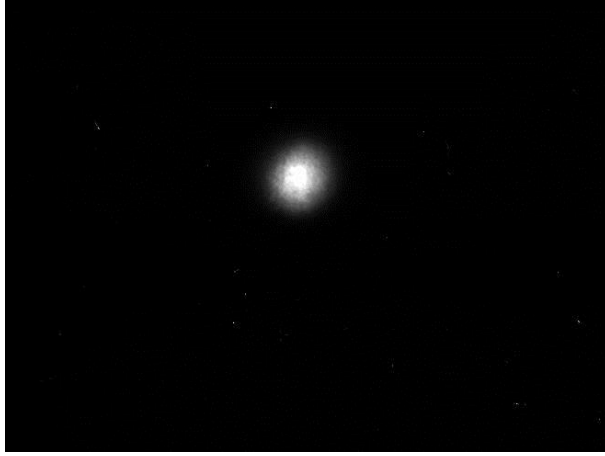


FIGURE 6 Beam image acquired by OTR camera at the 90° bend exit.

After setting up the proper current for the bends and quadrupole lenses used, we performed a set of beam measurements. The goal of the first experimental study was to estimate an energy acceptance range of the assembled bend. The earlier calculation, based on the existing equipment, showed that the dynamical aperture of the prototype is expected to be ± 1.5 MeV for a 38 MeV electron beam. The beam energy profile is represented by the violet curve in Figure 7. Due to the specification of a long injector pulse (about 5 microseconds), the acceleration of the beam produces a long low intensity tail in the low energy region.

For a beam with this energy spectrum, we determined the transport coefficient versus 90° bend optimum beam energy. Figure 7 shows smoothed beam energy profiles and calculated envelopes for electrons with various deviations from the optimal energy. The measured points are close to the estimated aperture restriction for the ± 1.5 MeV beam energy. Deviation of the measurements from the calculated curve is due to unaccounted edge effects, misalignments of the magnets and vacuum chamber, and systematic error in estimating the beam parameters.

The goal of the next experimental runs was to establish the dynamical stability of an electron beam on the reference trajectory. To meet this goal, the end was tuned up to a fixed beam energy of 36.5 MeV. After that, the beam energy was increased and decreased by changing the injector pulse amplitude while monitoring the total beam current and its displacement from the initial position. The exact beam position was measured by the OTR camera, which has a resolution of 0.117 mm per pixel. The total beam current was measured with a water-cooled aluminum beam stop, installed after the output window. Experimental results are presented in Figure 8. The beam displacement is less than 1 mm for energy deviation of ± 1.5 MeV ($\pm 4.2\%$). Beam intensity loss is less than 18% for energy offset of ± 1.0 MeV ($\pm 2.7\%$), and less than 8% with energy offset of ± 0.5 MeV ($\pm 1.4\%$).

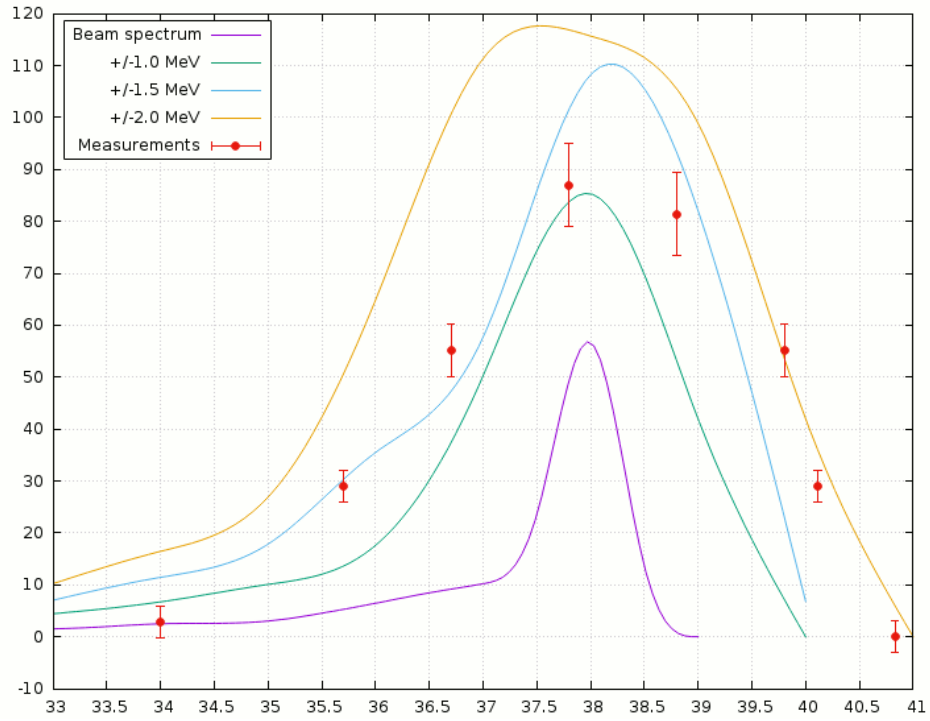


FIGURE 7 Beam intensity after passing of 90° bend based on beam energy spread vs. settings of 90° bend for separate energies.

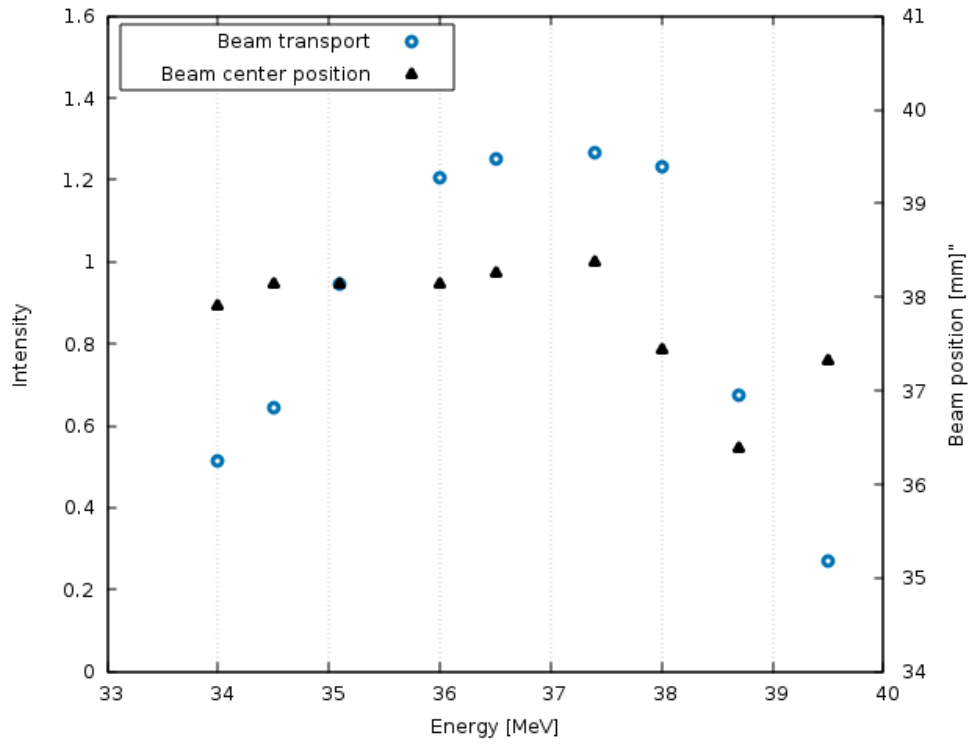


FIGURE 8 Changing of beam horizontal position and transport coefficient versus energy deviation.

6 CONCLUSIONS

Using a 90° bend for the isotope production facility would reduce the activation of the accelerator's components and would thereby allow shielding implementation for accelerators. Experimental measurements of the 90° achromatic bend showed good agreement with the design simulation. This design can be used for the non-dispersion bending system of the beam line for the Mo-99 production facility. Use of an accelerator with relatively narrow beam energy spread of $\pm 0.05\%$ full-width at half maximum, for example, the Rhodotron accelerator [5], will reduce the size and the cost of the achromatic 90° bend. The OTR camera is an excellent tool for permanent beam profile and position monitoring.

The excellent agreement with the design simulation notwithstanding, the test results have also shown that the initial design of the prototype can be improved. If the front and back edges of the main bending magnets were perpendicular to the beam pass, it would decrease the beam dispersion and, subsequently, the sizes and working currents of the compensating quadrupoles. Operation of the OTR camera in a high radiation environment requires good shielding for photons and neutrons.

7 REFERENCES

1. D. Rotsch, A. Youker, J. Krebs, M. Kalensky, P. Tkach, T. Heltemes, D. Stepinski, J. Byrnes, J. Jerden, W. Ebert, C. Pereira, M. Steindler, D. Bowers, S. Zaijin, S. Chemerisov, R. Gromov, V. Makarashvili, B. Miklich, C. Jonah, K. Woloshun, M. Holloway, F. Romero, J. Harvey, G. Dale, and G. Vandegrift, "Alternative Methods for the Production of Mo-99: Non-Fission Based Solid-State, Mo-100 (γ, n) Mo-99, and sub-Critical Solution-State, U-235 (n, f) Mo-99," *Proceedings of the Legacy Default Conference*, Columbia, MO, USA, 2014.
2. S. Chemerisov, G. Vandegrift, G. Dale, P. Tkach, R. Gromov, B. Miklich, C. Johan, V. Makarashvili, K. Woloshun, M. Holloway, F. Romero, and J. Harvey, "Accelerator Based Domestic Production of Mo-99: Photonuclear Approach," *Proceedings of the 2014 Mo-99 Topical Meeting*, Washington, DC, USA, 2014.
3. S. Chemerisov, M. Virgo, R. Gromov, and G. Vandegrift, "Beamline Design for High Power Radioisotope Production Facility," *Proceedings of Mo-99 2016 Topical Meeting*, St. Louis, MO, USA, 2016.
4. J. Bailey, S. Chemerisov, R. Gromov, R. Kmak, V. Makarashvili, G.F. Vandegrift, and M. Virgo, "High Energy, Beam Dump and Collimator for NorthStar," *Proceedings of 12th International Topical Meeting on the Nuclear Applications of Accelerators*, Washington, DC, USA, 2015.

5. IBA Industrial, <http://www.iba-industrial.com.cn/sites/default/files/White%20paper%20-%20Practical%20Advantages%20of%20the%20Rhodotron%20-%2020120112.pdf>.

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Nuclear Engineering Division

Argonne National Laboratory

9700 South Cass Avenue, Bldg. 208

Argonne, IL 60439-4854

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